Abstract

Carbon is an element that forms materials showing extraordinary properties. Diamond, for example, is among the hardest materials on earth, whereas graphite is soft and can be used as a lubricant. This simple comparison illustrates the broad spectrum of qualities that render carbon highly interesting for a plethora of applications. The different carbon forms (allotropes) have been the subject of fundamental research for many years in all fields of natural sciences. Although experiments on thin and even on single layers of graphite were performed long before, it was not until 2004 when graphene was brought into the spotlight. This year was the starting point of an intense graphene research conducted in many groups around the world.

Graphene is a single layer of carbon atoms structured in hexagonal rings possessing carbon bonds that are sp^2 hybridized. Theoretical considerations regarding the properties of graphene were already performed more than sixty years ago. Although it was not clear whether graphene can be synthesized, it constituted the theoretical building block for all known graphitic materials.

The aim of the presented work is to investigate different carbon nanostructures from the viewpoint of application as detectors or sensors. The purpose of the performed research was to design, process and characterize structures with the emphasis on fundamental properties and physical effects rather than the optimization of well known approaches. Three different structures that were based on epitaxial graphene grown on silicon carbide (SiC) and graphene naturally occurring on the surface of graphite were studied. Graphene is considered a promising candidate for sensing applications because of its excellent electrical properties, its two-dimensional character and its expected compatibility to organic molecules. The main idea which connects the three different approaches is the possibility to manipulate the charge carrier population of graphene by different external means (magnetic field, electric field, chemical environment).

For the first type of structures, epitaxial graphene on SiC grown at the Institute of Electronic Materials Technology (ITME) in Warsaw was employed. The optical lithography facilities available at the Faculty of Physics, University of Warsaw were used to fabricate a micrometer sized Hall bar structure. The metal contacts to the Hall bar were encapsulated with a special resin, so that the samples could be exposed to a solution. By taking advantage of the transparency of the SiC substrate in the visible wavelength range it was possible to perform Raman spectroscopy and to monitor the graphene resistance at the same time. The application of a voltage between the solution and the graphene allowed for the alternation of graphene's charge carrier concentration. The solution can here be seen as an equivalent to the dielectric in common field-effect transistors. A sweep in carrier concentration allowed us to study the electron-phonon coupling and led to the

first experimental observation of the resonant electron-phonon coupling effect of the G phonon for epitaxial bilayer graphene at room temperature. The observation of features related to the resonant coupling allowed for the extraction of the geometrical capacitance of the setup by taking into account the quantum capacitance of graphene. An application of larger gate voltages led to electrochemical reactions of graphene, which could be monitored using Raman spectroscopy. The Raman signatures related to this reaction could be identified as CH bonds, which was interpreted as a chemisorption of hydrogen on graphene. The process of chemisorption on graphene was further shown to be partially reversible.

For the second type of structures, a nitrogen ion implantation step was performed during a stay at the Australian National University in Canberra, prior to the actual epitaxial graphene growth process. The implanted layer gave rise to an n-type conductive layer inside the semi-insulating SiC substrate. This layer was used as a buried gate. The efficiency of this buried gate was studied with the use of magneto-transport measurements at low temperatures. The results proved successful gating.

The next system that was studied were carbon flakes occurring naturally on the surface of graphite showing a graphene-like behavior. A number of flakes were located and measured using Magneto-Raman experiments performed at the French National High Magnetic Field Laboratory (LNCMI) in Grenoble. The flakes were identified by mapping the surface and by monitoring the Raman signal for characteristic shifts present due to the magneto-phonon resonance at a constant magnetic field of $B = 10\,\text{T}$. By sweeping the magnetic field up to $14\,\text{T}$ we could observe the evolution of the magneto-phonon resonance and a new kind of coupling of the electronic inter-Landau level transitions to phonons, which had not been observed before. Many flakes were measured and analyzed, which resulted in statistics on Fermi velocities. Whenever substandard Fermi velocities were observed, a strong asymmetry in the peak shape of the inter-Landau level transitions was present. The described findings show that Raman-based Landau level spectroscopy is a powerful tool that can be used to assess the interactions of graphene with a substrate.

The results obtained on the three types of structures are set in the context of sensing applications and are discussed in the conclusions of this work.